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13. ABSTRACT*(Maximum 200 words)*

Under the support from ARO (DAAD19-99-1-0333), we have obtained three major achievements, including [1] dynamic aperture for THz wave microscopic imaging (see annual report 2001), [2] using THz wave for chemical & biological sensing activities (see annual report 2002), and [3] the development of the pulsed tomographic imaging technology.

In this final report, I present the recent development of our free-space THz wave imaging and its application. This report gives an overview of our ARO supported THz tomographic imaging project and its related science and technology.

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# FREE-SPACE IMAGING TECHNOLOY FOR THz BEAMS

X.-C Zhang
Center for Terahertz Research
Department of Physics, Applied Physics, and Astronomy, and
Department of Electrical, Computer and System Engineering
Rensselaer Polytechnic Institute, Troy, NY 12180-3590
Tel: (518) 276-3079; Fax: (518) 276-3292
Email: zhangxc@rpi.edu

Under the support from ARO (DAAD19-99-1-0333), we have obtained three major achievements, including [1] dynamic aperture for THz wave microscopic imaging (see annual report 2001), [2] using THz wave for chemical & biological sensing activities (see annual report 2002), and [3] the development of the pulsed tomographic imaging technology.

In this final report, I present the recent development of our free-space THz wave imaging and its application. This report gives an overview of our ARO supported THz tomographic imaging project and its related science and technology.

A THz wave tomographic imaging system is capable to provide real-time, large-scale, long-distance, three-dimensional (3D) images. Like conventional X-ray CT systems, the THz system will provide 3D mapping of structured objects, but without subjecting biological tissue to harmful radiation. In addition, it will offer important spectroscopic information that conventional systems cannot supply. The instrumentation will provide real-time images across an ultra-wide frequency band, extending from 100 gigahertz to 10 THz, at a variable frame rate from single-shot up to 1,000 frames per second, and it will be able to non-invasively image moving objects, turbulent flows, or explosions.

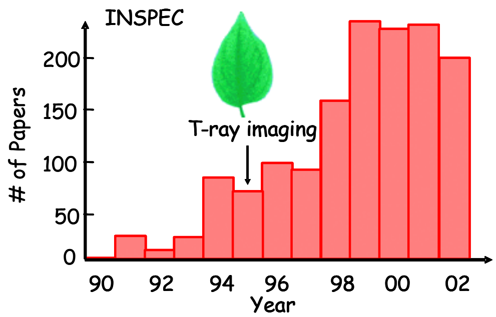
## I. BACKGROUND

Terahertz (THz) waves, a form of electromagnetic radiation, occupy a large portion of the electromagnetic spectrum between the infrared and microwave bands. THz time-domain spectroscopy and related THz technologies can help us view the world in new ways, because they offer innovative imaging and sensing technologies that can provide information not available through such conventional methods as microwave and X-ray.

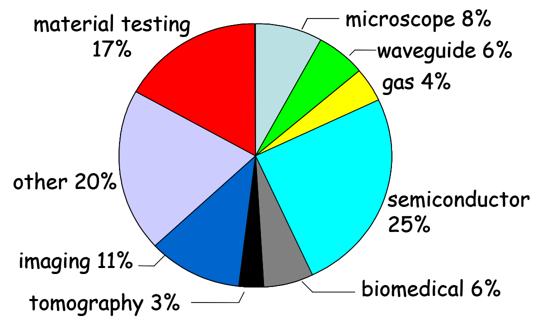
Compared to the relatively well-understood science and technology in microwave and optical frequencies, however, basic THz science and technology is in its infancy. There is, for example, no database of the spectral response of biomedical samples in the THz frequency range.

As THz wave (T-ray) technology improves, it has the potential to impact an almost limitless number of interdisciplinary fields, including communications, microelectronics, imaging, medical diagnosis, health monitoring, environmental control, agriculture, forensic science, and chemical and biological identification [1]. The explosion of interest in this once ignored field is shown by the fact that 1,400 pulsed THz wave papers have been published since 1990 (see Figure 1(a)). Figure 1(b) illustrates how these papers have been spread over a wide range of applications.

This rapid growth in interest in T-Ray technology has been spurred by the potential of a new sensing and imaging technology that offers major advantages over equipment now in use. T-rays have low-photon energies (4 meV @ 1 THz, for example,) and therefore do not subject biological tissue to harmful radiation [2]. In comparison, typical x-ray photon energy is in the range of keV, which is 1 million times stronger than the energy of THz wave photons. In addition, microwave and X-ray imaging modalities produce only density pictures, while THz wave imaging also provides spectroscopic information within the THz frequency range. The unique rotational, vibrational, and translational responses of materials within the THz range provide information that is generally absent in optical, X-ray, and NMR images. In principle, these transitions are highly specific to the molecule and therefore enable fingerprinting with THz-waves.




(a)




(b)

Fig. 1(a). INSPEC shows that over 1,400 papers in pulsed THz generation, detection, propagation, and application were published since 1990. (b). The field distribution among the papers collected from leading journals during the past 6 years. Even though the percentage of papers on THz imaging is low, it has increased rapidly in recent years.

Since the onset of pulsed THz wave imaging in 1995 [3], various THz-wave imaging modalities have been proposed, developed, and demonstrated for numerous applications [4-37]. They include electro-optic imaging [4], time-of-flight imaging [6], single-shot imaging [10], near-field imaging [16,21], dark-field imaging [27], bistatic THz-wave imaging [33,34] and THz-wave computed tomography (CT) [36-38]. Reports on the development of selected pulsed THz-wave imaging modalities since 1995 include:

- B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," *Optics Letters,* **20**, 1716, 1995.
- Q. Wu, T. D. Hewitt, and X.-C. Zhang, "Two-dimensional electro-optic imaging of terahertz beams," *Applied Physics Letters,* **69**, 1026, 1996.
- D. M. Mittleman, S. Hunsche, L. Boivin, and M. C. Nuss, "THz wave tomography," *Optics Letters,* **22**, 904, 1997.
- Z. Jiang and X.-C. Zhang, "Free-space electro-optic sampling of THz radiation with chirped optical beam," in *Ultrafast Phenomena XI*, 63, 197, Springer-Verlag, Berlin, 1998.
- B. Ruffin, J. Decker, L. Sanchez-Palencia, L. Le Hors, J. F. Whitaker, T. B. Norris, and J. V. Rudd, "Time reversal and object reconstruction with single-cycle pulses," *Optics Letters,* **26**, 681, 2001.

- T. D. Dorney, J. L. Johnson, J. V. Rudd, R. G. Baraniuk, W. W. Symes, and D. M. Mittleman, "Terahertz reflection imaging using Kirchoff migration," *Optics Letters,* **26**, 1513, 2001.
- B. Ferguson, S. Wang, D. Gray, D. Abbott, and X.-C. Zhang, "THz wave computed tomography," *Optics Letters,* **27**, 1312, 2002.
- THz Sensing and Imaging Technology, Ed. by D. Mittleman, Springer Series in Optical Sciences, Springer, New York, pp. 155-192, 2002.

## II. TERAHERTZ WAVE TOMOGRAPHY

Figure 2 schematically illustrates the concept. The target sample is mounted on a rotation stage, which allows it to be rotated, and a two-dimensional (2D) THz image is obtained at each projection angle.

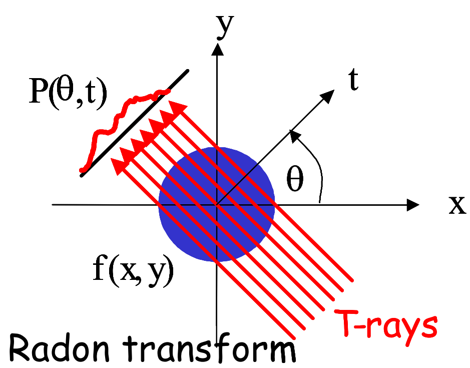



Fig. 2. Illustration of THz wave computed tomography. The target is scanned in the t direction and rotated. The detected signal is the line integral of the complex impedance (attenuation and phase) of the target. In this way, the spatial (x, y) domain is mapped to the domain (θ, t).

THz wave computed tomography is a novel technique for tomographic imaging with pulsed terahertz radiation. THz-wave CT extends THz imaging to the mapping of 3D structured objects. In addition to providing sectional images of objects in a manner analogous to conventional computed tomography techniques such as X-ray CT, the THz approach also provides spectroscopic information for target identification. THz-wave CT is inspired by the now ubiquitous X-ray CT system. The hardware is a relatively simple extension of modern transmission-mode THz imaging systems.

The data can then be processed using the filtered back-projection algorithm to reconstruct the refractive index and absorption coefficient at every position within the sample volume by inverting the Radon transform:

$$P(\theta,t) = \int_{L(\theta,t)} f(x,y)dl = R(f(x,y)), \tag{1}$$

The Radon transform assumes a shadow model and does not consider diffraction effects, nor does it account for the direction dependent Fresnel loss encountered in THz-wave CT. In Eqn. (1), $P$ is the measured projection data, $\theta$ is the projection angle, $t$ is the horizontal offset of the

projection from the axis of rotation, and *f(x, y)* is the projected slice of the sample that we wish to reconstruct. The measured data is assumed to be a simple line integral. This reconstruction algorithm can be performed to reconstruct a number of features from the measured data depending on the desired application. The amplitude of the THz pulse and the timing of the peak of the pulse are prime examples. The reconstructed amplitude image gives a 3D image, which depends on the bulk absorption of the sample in the far-infrared (including Fresnel losses) while the reconstructed timing image provides a refractive index map of the sample in 3D. Using the phase information, which is equivalent to the timing of the scattered THz pulse, leads to a 3D image of the index of refraction.

In the typical *pulsed* THz wave real-time imaging system, THz pulses are generated using a regeneratively amplified Ti:sapphire laser incident on a wide-aperture biased photoconductive antenna. The laser delivers pulses of 800 nm (near-infrared) light with a pulse width of 100 femtoseconds. The laser pulses trigger a photocurrent in a GaAs photoconductive antenna, which results in the emission of broadband pulses of THz radiation. The THz radiation is then focused and transmitted through the target.

Using telescope lenses, the pump and probe beams are expanded to a diameter larger than the target. The transmitted THz pulse is measured using 2D EO sampling, where it modulates the polarization of the probe pulse in a <110> ZnTe EO detector crystal. The polarization-analyzed probe pulse is then detected using a CCD camera. The frame rate of this camera theoretically will allow a full 3D target to be imaged within one minute.

Data acquisition speed is an important concern in all THz imaging systems, and it is of particular concern for THz-wave CT because multiple images of the object must be obtained. For this reason a linearly chirped optical probe beam is used for EO detection of the THz pulses [8]. By using this technique, the full THz waveform is measured simultaneously, dramatically accelerating the imaging speed. The target is then raster scanned in *x* and *y* dimensions to form a 2D image. This technique is still quite time-consuming; a typical image of 100x100 pixels measured at 18 projection angles can take over an hour. Fortunately, there are several methods available to improve this speed. Performing 2D THz imaging with a high speed CCD camera (1825 frames/second) may potentially reduce the acquisition time to a few seconds.

## II. RECONSTRUCTING THE IMAGES

The reconstruction of the 3D object from the measured projection data is performed using mathematical inverse algorithms. THz-wave CT borrows algorithms from the well-established field of X-ray CT. The filtered back-projection algorithm has long been the workhorse in this domain. It is used to invert the Radon transform to reconstruct the object of interest. For THz-wave CT, the detected THz signal can be approximated by a line integral of the form

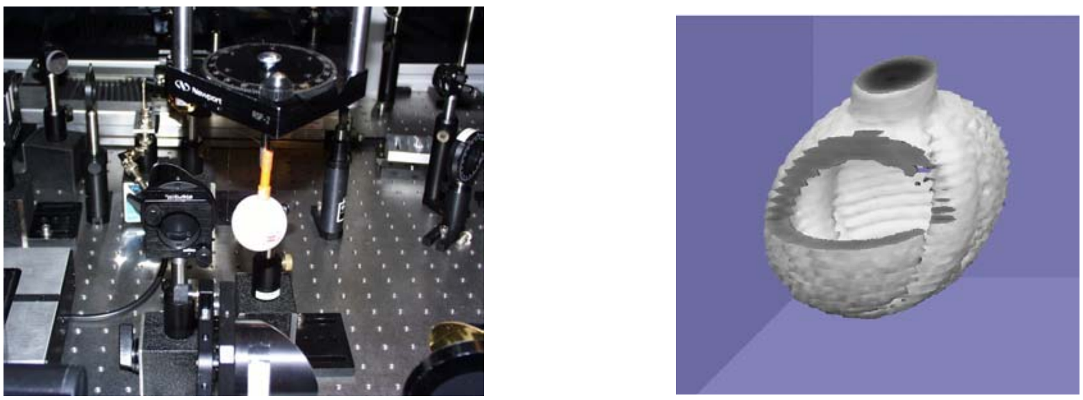
$$P_d(\theta, t) = P_t \exp\left[\int_{L(\theta,t)} \frac{i\omega n(x)}{c} dx\right], \tag{2}$$

where $P_d(\theta, t)$ is the detected THz signal at a projection angle, $\theta$, and a horizontal offset from the axis of rotation, $t$. The incident THz signal is $P_t$, $L$ is the straight line between the source and detector, $\omega$ is the angular THz frequency, and $n(x)$ is the unknown complex refractive index of

the sample. The filtered back-projection algorithm is then used to compute *n* using the measured projection data. This method contains a number of implicit assumptions that are only valid in approximation, but it serves well when reconstructing objects of simple geometry.

Unlike traditional X-ray CT, which only measures the amplitude of the transmitted radiation, THz-wave CT measures the transmitted pulse shape. This allows us to gain more information about the object, such as the index of refraction. Using the timing (or phase) will reconstruct a refractive index map of the sample in 3D. Full reconstruction algorithms may use the Fourier transform of the measured THz pulses to reconstruct the *frequency-dependent* refractive index and absorption of the sample. This may then allow different materials to be identified.

To demonstrate the feasibility of 3D reconstruction, we have tested a hollow dielectric sphere using a 1 mm step size and 18 different projection angles (see Figure 3(a)). The amplitude of the THz pulse for each projection was used to reconstruct the sphere as can be seen in Fig. 3(b). The basic shape of the sphere and the affixed plastic rod is clearly visible. Part of the data was cut away to allow the interior to be viewed.



(a) (b)

Fig. 3(a). A hollow dielectric sphere is imaged using THz-wave CT. The sphere is attached to a plastic rod, which is rotated by the rotation stage. The sphere was scanned with a 1 mm step size, and a THz image was obtained for 18 different projection angles. 3(b) The amplitude of the THz pulse at each pixel of the sphere was used as the input to the filtered back-projection algorithm. Each horizontal slice of the sphere was reconstructed, and the slices were combined and rendered to form a 3D image.

(a) (b)

Fig. 4. (a). A piece of turkey bone is imaged using the THz-wave CT system. The fine structure inside the bone is of the order of the THz wavelength and therefore causes difficulties in reconstruction; 4(b). 3D image of the turkey bone. The reconstruction used the amplitude of the THz pulses at each pixel as the input to the filtered back-projection algorithm.

Figure 4(a) shows an optical photograph of a complex target, a piece of turkey bone. This sample was imaged using the THz-wave CT system, and the amplitude of the measured THz pulses was used to reconstruct the bone. It is obvious that although the outer profile has been reconstructed with reasonable accuracy, the fine internal structure was not recovered. The reconstructed 3D THz image is shown in Fig. 4(b). Because of Abbe's principle, the fine structure of the inner bone could not be resolved.

## III. THZ TOMOGRAPHIC IMAGING WITH A FRESNEL LENS

We have demonstrated small-scale 3D tomographic imaging using a silicon Fresnel lens (2-cm diameter, focal length f = 2.5 cm) and broadband THz pulses [39]. Fresnel lenses have a frequency dependent focal length. Thus, the distances to the objects become frequency-encoded, and depth-dependant images are formed at specific frequencies. This approach allows the reconstruction of an object's tomographic contrast image by assembling the frequency-dependent images, as shown in Figure 5.

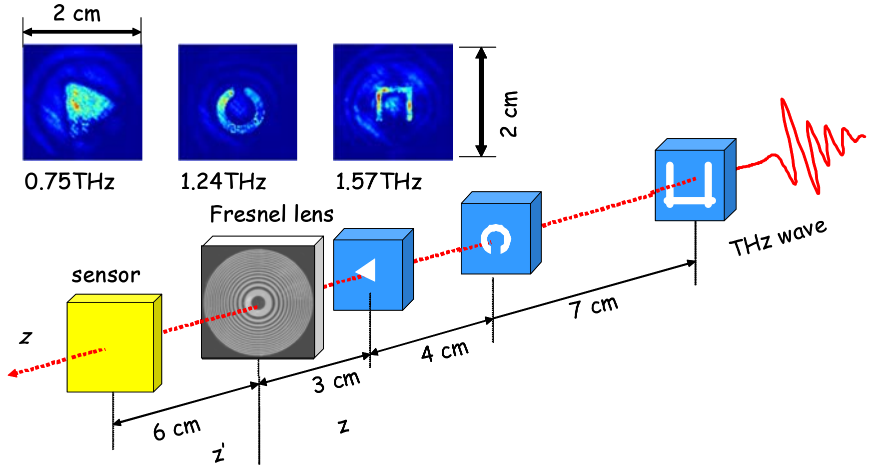



Fig. 5. Schematic illustration of tomographic imaging with a Fresnel lens. Three targets were placed at 3 cm, 7 cm, and 14 cm away from the Fresnel lens. The multiple patterns are imaged on the sensor at a distance of 6 cm from the Fresnel lens, with inverted tomography images of the patterns at the frequencies of 0.75 THz, 1.24 THz and 1.57 THz, respectively.

## IV. LIMITATIONS OF THZ TOMOGRAPHIC IMAGING

Current T-ray tomographic techniques are still limited to the small-scale laboratory. *The bottleneck is the signal-to-noise ratio (SNR)*. Major limitations, which result from low SNR, include:

- Long data acquisition time: It takes many tens of minutes to hours to take one image.
- Short imaging distance: Current systems require small targets within tens of cm of the THz source.

- Limited T-ray power for large-scale imaging: Except free-electron lasers, most T-ray sources are relatively low power.
- Lack of THz-wave imaging components: Unlike in optical imaging, high quality T-ray imaging components, such as lenses and polarizers, are not well developed.

Other challenges that we must overcome in the design, assembly, and fabrication of the tomographic imaging system include the need for:

- A high-speed, high-voltage bipolar power supply: A power supply with ±100,000 V at 10 to 30 Hz rate for the photoconductive antenna.
- Large diameter plastic Fresnel binary lenses: A THz lens with a diameter up to 0.5 meter and a focal length of 2 meters for an imaging distance greater than 10 meters.
- Long distance temporal delay stage: A travel distance for more than 1 meter at 1 to 10 Hz, with target distance greater than 100 meter for pulsed THz imaging.

## V. Conclusion

Imaging with a continuous wave laser has been successfully demonstrated previously in sub-mm wave range [40-45]. To our best knowledge, pulsed THz wave has not been used for tomographic imaging applications. Potentially, the coherent measurement of time-domain with phase and timing data provides tomographic imaging with spectroscopic information.

## References


[1] B. Ferguson and X.-C. Zhang, "Materials for THz science and technology," *Nature Materials* **1**, 26, 2002.

[2] S. W. Smye, J. M. Chamberlain, A. J. Fitzgerald, and E. Berry, "The interaction between terahertz radiation and biological tissue," *Physics in Medicine and Biology* **46**(9), pp. R101–R112, 2001.

[3] B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," *Optics Letters* **20**(16), pp. 1716–1718, 1995.

[4] Q. Wu, T. D. Hewitt, and X.-C. Zhang, "Two-dimensional electro-optic imaging of terahertz beams," *Applied Physics Letters* **69**(8), pp. 1026–1028, 1996.

[5] Q. Wu, F. G. Sun, P. Campbell, and X.-C. Zhang, "Dynamic range of an electro-optic field sensor and its imaging applications," *Applied Physics Letters* **68**(23), 3224-3226, 1996.

[6] D. M. Mittleman, R. H. Jacobson, and M. C. Nuss, "T-ray imaging," *IEEE Journal of Selected Topics in Quantum Electronics* **2**(3), pp. 679–692, 1996.

[7] D. M. Mittleman, S. Hunsche, L. Boivin, and M. C. Nuss, "T-ray tomography," *Optics Letters* **22**(12), pp. 904–906, 1997.

[8] Z. Jiang and X.-C. Zhang, "Free-space electro-optic sampling of THz radiation with chirped optical beam," in *Ultrafast Phenomena XI*, **63**, 197, Springer-Verlag, Berlin, 1998.

[9] S. Hunsche, M. Koch, I. Brener, and M. C. Nuss, "THz near-field imaging," *Optics Communications,* **150**(1–6), pp. 22–26, 1998.

[10] Z. Jiang and X.-C. Zhang, "Single-shot spatiotemporal terahertz field imaging," *Optics Letters* **23**(14), pp. 1114–1116, 1998.

[11] D. D. Arnone, C. M. Ciesla, A. Corchia, S. Egusa, M. Pepper, J. M. Chamberlain, C. Bezant, E. H. Linfield, R. Clothier, and N. Khammo, "Applications of terahertz (THz) technology to medical imaging," in *Terahertz Spectroscopy and Applications*, **3828**, pp. 209–219, SPIE, (Munich, Germany), 1999.

[12] Q. Chen, Z. Jiang, and X.-C. Zhang, "All-optical THz imaging," in *Proceedings of SPIE*, **3617**, pp. 98–105, 1999.

[13] Z. Jiang and X.-C. Zhang, "Terahertz imaging via electro-optic effect," *IEEE Transactions on Microwave Theory and Techniques* **47**(12), pp. 2644–2650, 1999.

[14] M. Koch, "THz imaging: Fundamentals and biological applications," in *Proceedings of SPIE – Conference on Terahertz Spectroscopy and Applications*, **3828**, pp. 202–208, SPIE, (Munich, Germany), 1999.

[15] D. M. Mittleman, M. Gupta, R. Neelamani, R. G. Baraniuk, J. V. Rudd, and M. Koch, "Recent advances in terahertz imaging," *Applied Physics B: Lasers and Optics* **68**(6), pp. 1085–1094, 1999.

[16] Q. Chen, Z. Jiang, G. X. Xu, and X.-C. Zhang, "Near-field terahertz imaging with a dynamic aperture," *Optics Letters* **25**(15), pp. 1122–1124, 2000.

[17] P. Y. Han, G. C. Cho, and X.-C. Zhang, "Time-domain transillumination of biological tissues with terahertz pulses," *Optics Letters* **25**(4), pp. 242–244, 2000.

[18] Z. Jiang, X. G. Xu, and X.-C. Zhang, “Improvement of terahertz imaging with a dynamic subtraction technique,” *Applied Optics* **39**(17), pp. 2982–2987, 2000.

[19] Z. Jiang and X.-C. Zhang, “Measurement of spatio-temporal terahertz field distribution by using chirped pulse technology,” *IEEE Journal of Quantum Electronics* **36**(10), pp. 1214–1222, 2000.

[20] S. Mickan, D. Abbott, J. Munch, X. C. Zhang, and T. van Doorn, “Analysis of system trade-offs for terahertz imaging,” *Microelectronics Journal* **31**(7), pp. 503–514, 2000.

[21] Mitrofanov, I. Brener, R. Harel, J. D. Wynn, L. N. Pfeiffer, K. W. West, and J. Federici, “Terahertz near-field microscopy based on a collection mode detector,” *Applied Physics Letters* **77**(22), pp. 3496–3498, 2000

[22] B. Ferguson, S. Wang, D. Gray, D. Abbott, and X.-C. Zhang, “Terahertz imaging of biological tissue using a chirped probe pulse,” in *Electronics and Structures for MEMS II*, N. W. Bergmann, ed., *Proceedings of SPIE* **4591**, pp. 172–184, Adelaide, Australia, 2001.

[23] Q. Chen and X.-C. Zhang, “Semiconductor dynamic aperture for near-field terahertz wave imaging,” *IEEE Journal of Selected Topics in Quantum Electronics* **7**(4), pp. 608–614, 2001.

[24] Q. Chen, M. Tani, Z. Jiang, and X. C. Zhang, “Electro-optic transceivers for terahertz-wave applications,” *Journal of the Optical Society of America B: Optical Physics* **18**(6), pp. 823–831, 2001.

[25] J. L. Johnson, T. D. Dorney, and D. M. Mittleman, “Interferometric imaging with terahertz pulses,” *IEEE Journal of Selected Topics in Quantum Electronics* **7**(4), pp. 592–599, 2001.

[26] J. L. Johnson, T. D. Dorney, and D. M. Mittleman, “Enhanced depth resolution in terahertz imaging using phase-shift interferometry,” *Applied Physics Letters* **78**(6), pp. 835–837, 2001.

[27] T. Loffler, T. Bauer, K. J. Siebert, H. G. Roskos, A. Fitzgerald, and S. Czasch, “Terahertz dark-field imaging of biomedical tissue,” *Optics Express* **9**(12), 2001.

[28] K. McClatchey, M. T. Reiten, and R. A. Cheville, “Time resolved synthetic aperture terahertz impulse imaging,” *Applied Physics Letters* **79**(27), pp. 4485–4487, 2001.

[29] Mitrofanov, M. Lee, J. W. P. Hsu, I. Brener, R. Harel, J. F. Federici, J. D. Wynn, L. N. Pfeiffer, and K. W. West, “Collection-mode near-field imaging with 0.5-THz pulses,” *IEEE Journal of Selected Topics in Quantum Electronics* **7**(4), pp. 600–607, 2001.

[30] J. O’Hara and D. Grischkowsky, “Quasi-optic terahertz imaging,” *Optics Letters* **26**(23), pp. 1918–1920, 2001.

[31] A. B. Ruffin, J. Decker, L. Sanchez-Palencia, L. Le Hors, J. F. Whitaker, T. B. Norris, and J. V. Rudd, “Time reversal and object reconstruction with single-cycle pulses,” *Optics Letters* **26**(10), pp. 681–683, 2001

[32] R. M. Woodward, B. Cole, V. P. Walace, D. D. Arnone, R. Pye, E. H. Linfield, M. Pepper, and A. G. Davies, “Terahertz pulse imaging of in-vitro basal cell carcinoma samples,” in *Conference on Lasers and Electro-Optics 2001*, pp. 329–330, SPIE, 2001.

[33] T. D. Dorney, J. L. Johnson, J. V. Rudd, R. G. Baraniuk, W. W. Symes, and D. M. Mittleman, “Terahertz reflection imaging using Kirchoff migration,” *Optics Letters,* **26**(19), 1513, 2001.

[34] P. Planken, “A terahertz system using semi-large emitters: noise and performance characteristics,” in *Proceedings of Biomedical Imaging & Sensing Applications of Terahertz Technology*, Leeds, UK, 2001.

[35] M. Herrmann, M. Tani, K. Sakai, and R. Fukasawa, “Terahertz imaging of silicon wafers,” *Journal of Applied Physics* **91**(3), pp. 1247–1250, 2002.

[36] B. Ferguson, S. H. Wang, and X.-C. Zhang, “T-ray computed tomography,” Post deadline Paper, PD1.7 in IEEE/LEOS Annual Meeting, San Jose, CA, 2001.

[37] B. Ferguson, S. H. Wang, D. Gray, D. Abbott and X.-C. Zhang, “Towards functional 3D T-ray imaging,” *Physics in Medicine & Biology,* **47**, pp. 3735-3742, 2002.

[38] B. Ferguson, S. H. Wang, D. Gray, D. Abbott and X.-C. Zhang, “T-ray computed tomography,” *Optics Letters*, **27**(15), pp. 1312-1314, 2002.

[39] S. H. Wang and X.-C. Zhang, “Terahertz tomographic imaging with a Fresnel lens,” *Optics & Photonics News*, Special December issue, "Optics in 2002." **13**(12) 59, 2002.

[40] F. Keilmann, F. K. Renk, "Visual observation of submillimeter wave laser beams," *Applied Physics Letters,* **18**(6), pp. 452-454, 1971.

[41] N. I. Malykh, A. G. Nagornyi, and E. S. Yampol’skii, “Submillimeter-wave imagery,” *Instruments and Experimental Techniques*, **18**(1) pp. 182-184, 1975.

[42] T. S. Hartwick, D. T. Hodges, D. H. Barker, F. B. Foote, "Far infrared imagery," *Applied Optics,* **15**(8), pp. 1919-1922, 1976.

[43] T. S. Hartwick, "Far infrared imaging techniques for law enforcement applications," Proc. Society of Photo-Optical Instrumentation Engineers, **108**, Optics in Security and Law Enforcement, Bellingham, WA, pp 139-140, 1977.

[44] P. K. Cheo, "Far infrared imaging for quality control," Proc. Society of Photo-Optical Instrumentation Engineers, **105**, Far Infrared / Submillimeter Wave, Bellingham, WA, p. 117, 1977.

[45] A. A. Lash, D. N. Yundev, "Visualization of submillimeter laser radiation with a pyroelectric television camera," *International Journal of Infrared and Millimeter Waves*, 5(4), pp. 489-505, 1984